

A Geomechanical Model for Gas Shales Based on the Integration of Stress Measurements and Petrophysical Data from the greater Marcellus Gas System

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Executive Summary: The purpose of this report is to describe the activities between December 2011 and June 2012 for a project 09122-32 funded by RPSEA, titled “A Geomechanical Model for Gas Shales Based on the Integration of Stress Measurements and Petrophysical Data from the greater Marcellus Gas System”. Major technical progress involves defining the mechanical stratigraphy based on fracture toughness of the Marcellus black shale. The fracture toughness of Middle Devonian core samples is heavily influenced by lithology, mineralogy, and organic content. Sandstones and quartz-rich samples have the highest fracture toughness while clay and organic-rich black shales have the lowest fracture toughness in this study.

Introduction

In brief, the initial objectives of RPSEA project 09122-32 are threefold. First is the collection of stress profiles in three wells through the Marcellus gas system. This is an extension of the South Canisteo experiment (Evans et al., 1989; Plumb et al., 1991). Second was the interpretation of the stress profile by the integration of our stress data employing a full suite of log- and core-based petrophysical data. Third was the development of a geomechanical model for use by industry when engineering stimulations are required to enhance performance within the Marcellus gas system. These three objects were outlined in tasks 5, 6, and 7, respectively, of the following project management plan (listed next).

Since writing original project management plan, experiments by Chesapeake and Schlumberger have revealed that a critical element of the Schlumberger MDT, the packers, would fail under a differential pressure of 4000 psi. Discussion of various options took place during an April 18, 2012 meeting among Range Resources, Schlumberger, and Penn State. In summary, Range Resources has proposed a virtually identical suite of measurements with the exception of the MDT stress tests. These measurements will take place in October of 2012. In lieu of the stress tests, Range has proposed to provide access to fracture initiation and ISIP data from fracture stimulation stages conducted by Range

in the Cornwall "A" Unit No. 1H and the Laurel Hill Game Club No. 1H well. These data will be supplied at no cost to RPSEA. In exchange, Range will leave it to Penn State's discretion to select an ancillary experiment to supplement these data using RPSEA funds. Penn State's choice shall be a microseismic experiment using both Global Geophysical and Microseismic Inc. as primary subcontractors.

Major technical problems with the MDT stress tests:

Stress tests using the Schlumberger MDT tool have been attempted in collaboration between Chesapeake and Schlumberger. It was found that Schlumberger MDT tool could not hold a differential stress across packers of much above 4000 psi. This limitation hampers the ability of the Schlumberger MDT tool to break the formation down at depths of the Marcellus where breakdown in horizontal wells can exceed 12,000 psi (9,000 psi surface pressure). Breakdown pressure can be increased by filling the borehole with a drilling mud of, say, 12#/gal (heavier muds are more expensive).

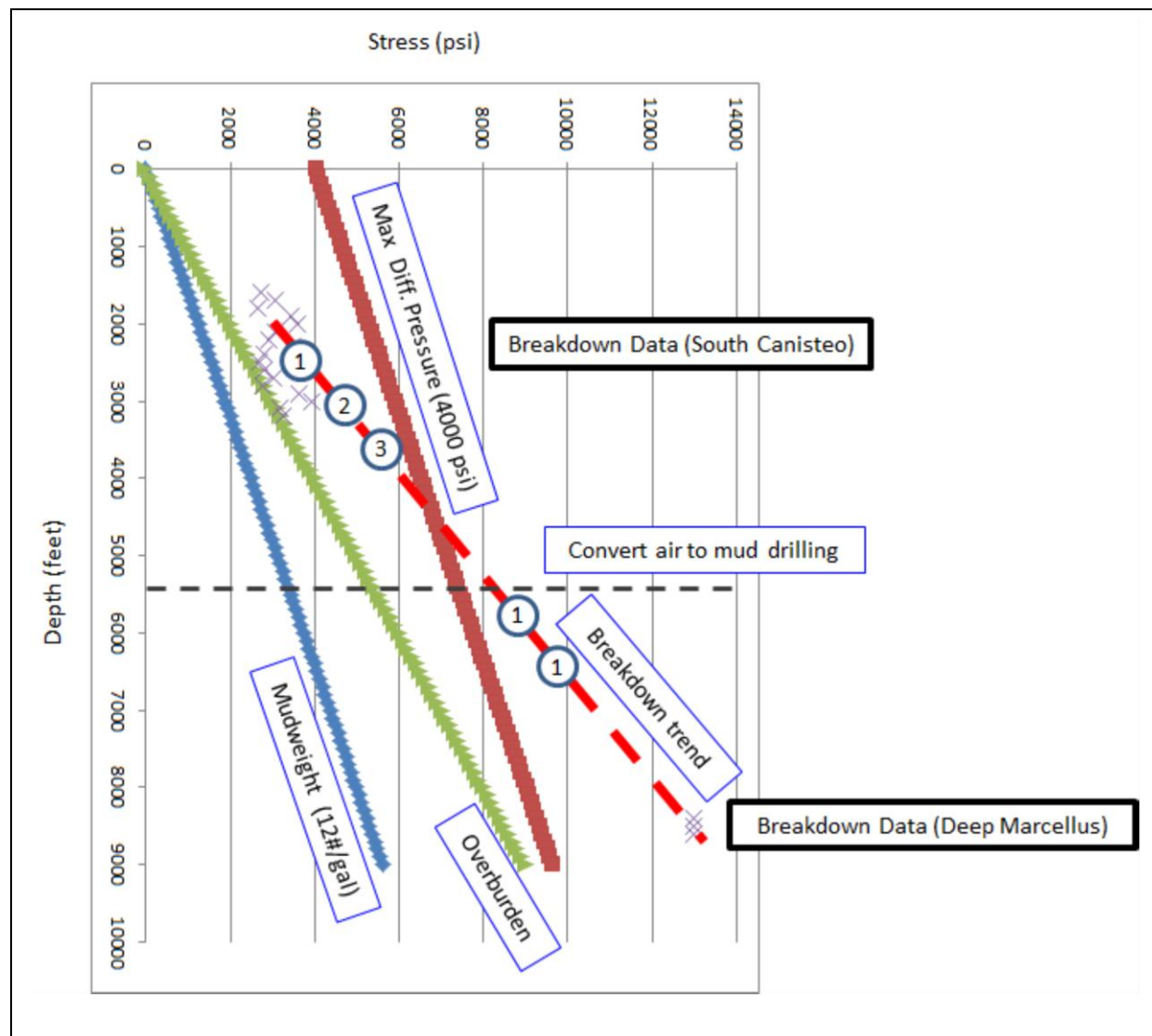


Figure 1 shows the pressure of a 12#/gal mud as a function of depth in a borehole. The maximum pressure that can be generated to reach a differential pressure across the packers is a line with the slope of the mud pressure plus 4000 psi. Breakdown pressure for the South Canisteo experiments are shown at depths between 2000 and 3000 feet. Breakdown in deep Marcellus wells are shown at depths of 8500 feet. These two breakdown clusters are connected by a dashed line. A conversion from air to mud-based drilling is proposed for 5,500 feet. The crossover between the maximum differential pressure on the packers and the theoretical breakdown pressure is about 4,500 feet or about 1000 feet above the conversion from air to mud drilling.

Based on the behavior of the MDT tool, the following experiment might be proposed. Schlumberger shall be contracted to provide a minimum of 14 MDT sets for stress measurements. Because the targets of greatest interest are outside the range of unaided breakdown for the MDT tool, it seems prudent to attempt three (#1 - #3) MDT sets in the air drilled portion of the borehole despite the relatively rougher borehole wall (Figure 1). How these three sets are located is left to negotiation based on the logs available at the time of initial logging of the Cornwall hole.

Range Resources Proposal as of June 11, 2012

Range Resources have reviewed the RPSEA project for "A Geomechanical Model for Gas Shales Based on the Integration of Stress Measurements and Petrophysical Data from the Greater Marcellus Shale System" as it applies to the Range Resources Appalachia L.L.C. Cornwall "A" Unit No. 1H and have an alternative to open-hole stress tests with Schlumberger's MDT tool in a dual packer configuration. The Cornwall "A" Unit No. 1H is marginally economic for Range Resources Appalachia L.L.C. to drill and complete without the additional pilot hole and the RPSEA project costs because of high location costs and low natural gas prices. The success of collecting stress data with the MDT tool is very questionable and probably unlikely in the deeper part of the hole. We discussed on April 18th, 2012 attempting open-hole stress tests with the drilling rig - with a packer in the drill string and using the rig pumps.

Range Resources Appalachia L.L.C. will instead contribute the following to the project:

- 1) Pilot hole log data from the Cornwall "A" Unit No. 1H pilot hole including Platform Express, ECS, Sonic Scanner, and FMI
- 2) Rotary sidewall core data from the Cornwall "A" Unit No. 1H pilot hole including XRD, petrography, Tight Rock Analyses (porosity, permeability, and saturations), TOC, Rock-Eval, static stress tests, and ultrasonic velocity
- 3) Access to all similar data from the Range Resources Appalachia L.L.C. Laurel Hill Game Club No. 1H pilot hole including the Marcellus core, also in Lycoming Co.
- 4) Access to fracture initiation and ISIP data from fracture stimulation stages conducted by Range in the Cornwall "A" Unit No. 1H and Laurel Hill Game Club No. 1H wells.

The proposed data contribution by Range Resources Appalachia L.L.C. will facilitate the development of the project model. Pennsylvania State University will be able to apply the RPSEA funding to other data collection.

Present Work Flow Plan

Task 5.0 – DATA COLLECTION

In collaboration among the project participants (researchers, operating companies and service companies) data on stress in the Marcellus shall be obtained in three wells (a feasibility well plus two follow on wells) distributed strategically about the Marcellus fairway.

Data collection involves a number of steps starting with collaboration involving the selection and planning of a test hole for each experiment. Plans call for the rotary sidewall core sampling in at least two of the three wells, including the feasibility well. After each of the three wells has been drilled, the PI will collaborate with service-company engineers while well logging and testing is taking place. Sampling shall include several logging runs using the following tools: platform express (or the equivalent) and ECS (Elemental Capture Spectrophysics), FMI (Formation Micro Imager) and Sonic Scanner. Stress in the Marcellus shall be obtained using breakdown and ISIP (Initial shut-in pressure) measurements in the horizontal portion of each well. Company FIT (formation integrity tests) from the area of the test well will be reviewed for leakoff and shut-in data for shallower horizons. The Rotary side wall cores will be used to collect the following data: SEM, Petrographic analyses, SRD, permeability, porosity, saturation analyses, sonic properties and static strength tests. These data shall be supplemented with surface microseismic data taken from either a patch or star array, from an area located centered around the well.

Task 6.0 – DATA ANALYSIS

In preparation for the analysis of data from the wells, the Penn State Appalachian Basin Black Shale Group (ABBSG) log library will be analyzed for a basin-wide stress model. This shall involve placing petrophysical data into Petrel, the Schlumberger reservoir simulator. As seismic data becomes available, these data will also be incorporated in Petrel.

The second step in data analysis involves specific stress measurements with components being the interpretation of the pressure-time curves for in situ stress and the interpretation of petrophysical logs for mechanical properties. Finally the data analyses will involve the correlation of in situ stress with petrophysical properties. These data will be prepared for entry into our geomechanical model (Task 7.0).

Task 7.0 – GEOMECHANICAL MODEL

Specific well data collected will be incorporated along with interpreted data into a model developed for the Appalachian Basin. The platform by which this will be accomplished is Schlumberger's Petrel. This will lead to a mechanical model for the relationship between TOC, density, and in situ stress. We are particularly interested in joining Petrel's capability in facies modeling with fracturing modeling with the idea that mechanical properties and stress are facies dependent. Part of this work involves the use of breakdown pressure and shut in pressure, mainly from horizontal wells, to develop a fracture mechanics model for the Marcellus shale with particular focus on specific facies within the Marcellus shale.

First Seven Months of the Project:

Effort during the first seven months of the project were split between planning for the first field experiment as described above (Tasks 5 and 6) and developing a skill set to manage the Petrel data and develop a geomechanical model (Task 7). Most progress was made on developing a geomechanical model for the Marcellus based on fracture mechanics and the fracture toughness of Marcellus cores from the Penn State core lab (Figure 2).

Gas production from the Marcellus shale of the Appalachian Basin relies on hydraulic fracture stimulation of a low permeability, organic-rich reservoir. The geomechanical properties of gas shales are considered critical factors in the drilling and production success of wells. A recent attempt has been made to merge the geomechanics and sequence stratigraphy of unconventional gas shales but this approach has yet to be applied to the Marcellus shale (Slatt and Abousleiman, 2011). This study is the first such endeavor and combines a detailed sequence stratigraphic model (Kohl, 2012) with a comprehensive series of laboratory tests to determine the geomechanical characteristics of over 900 samples from 6 core wells across the Appalachian Basin (Figure 2). Sequence stratigraphy is used to correlate parasequences and other significant surfaces (i.e., maximum flooding surface (MFS), maximum regressive surface (MRS), etc.) between the wells (Figure 3). I performed laboratory tests on core samples to determine the variation in mode-I fracture toughness, tensile strength, and elastic modulus of the correlated intervals.

The recent work by Slatt and Abousleiman (2012) to combine geomechanics and sequence stratigraphy also proposes that the presence of laminae/bedding planes act as planes of weakness that can affect drilling and hydraulic fracture stimulation. This study uses two bedding plane orientations, the arrester and divider geometries (from Schmidt, 1977), to determine what effect the presence of laminae has on the geomechanical properties. The arrester geometry applies a load perpendicular to bedding planes while the divider configuration loads the sample parallel to laminae (Figure 4). Due to the fissile nature of the Marcellus core samples, specimens with the short transverse geometry used by Schmidt (1977) could not be prepared for this study. In addition to the two bedding plane orientations, x-ray diffraction (XRD) and total organic carbon (TOC) analyses

were employed to determine the influence of mineralogy and organic content on the geomechanical properties of the core samples. One

The Marcellus Formation in Pennsylvania consists of three members (i.e., a lower Shamokin Member, informally called the Union Springs mbr.; a middle carbonate Purcell Mbr.; and an upper Unnamed member, henceforth referred to as the Oatka Creek mbr.) and comprises two 3rd order depositional sequences (Lash and Engelder, 2011). The basal Union Springs mbr. was deposited during the first 3rd order sequence, which is demarcated by unconformities in the underlying Selinsgrove Limestone (referred to in this study as the Onondaga Fm.) and at the base of the overlying Purcell Mbr. The second 3rd order sequence spans the Purcell and Oatka Creek members and terminates at a sequence boundary in the overlying Mahantango Fm. Core samples from each Marcellus member are included in this study but the majority of specimens come from the Union Springs mbr. because this member is most commonly the drilling and production target of industry. I paid particular attention to the MFS of the Union Springs mbr. as this surface has the highest gamma ray API values and is widely considered to have the highest TOC. Consequently, I sampled strata adjacent to this surface (or in the case of the Erb and Handiboe wells, intervals with comparable API and lithofacies) in the 5 wells displayed in Figure 3.

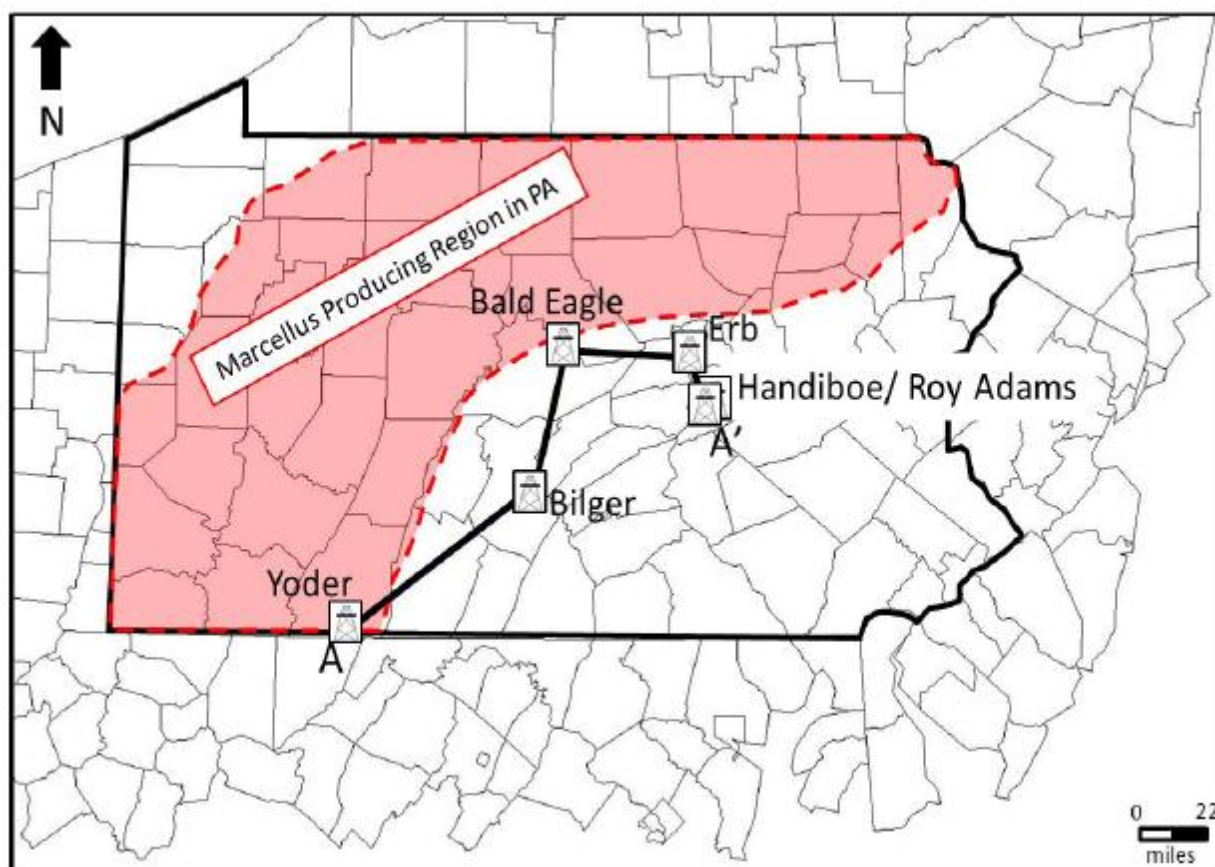


Figure 2. Map of the six core wells included in this study. The Yoder well is located in the Marcellus gas-producing Appalachian Plateau province while the other wells are in the thermally overmature, non-

prospective Valley and Ridge province of Pennsylvania. The approximate Marcellus gas-producing region in Pennsylvania is denoted by the red polygon. Sequence stratigraphic correlations (shown in Figure 2) are made along the line A-A'.

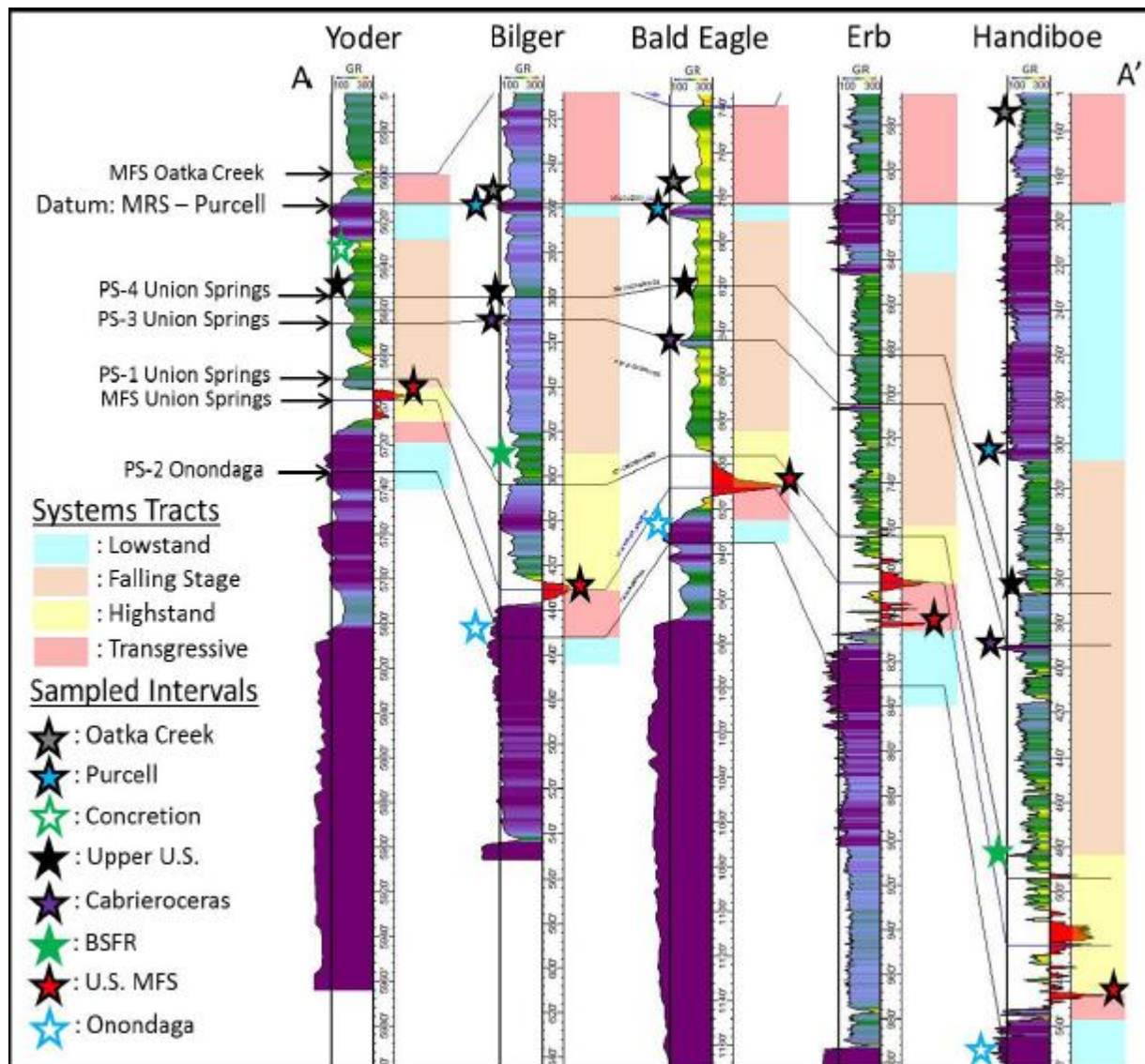


Figure 3. Gamma ray log correlations of sequence stratigraphic surfaces and intervals sampled in this study along line A-A' (location shown in Figure 2). The Roy Adams well is absent because it did not penetrate the Union Springs mbr. but was used for testing samples higher in the section. For simplicity, additional intervals tested in the study do not appear on this figure. Systems tract designations and sequence stratigraphic surfaces are from Kohl (2012). Gamma ray scale: 100 - 300 API, MFS = maximum flooding surface, MRS = maximum regressive surface, PS = parasequence, U.S. = Union Springs, BSFR = basal surface of forced regression.

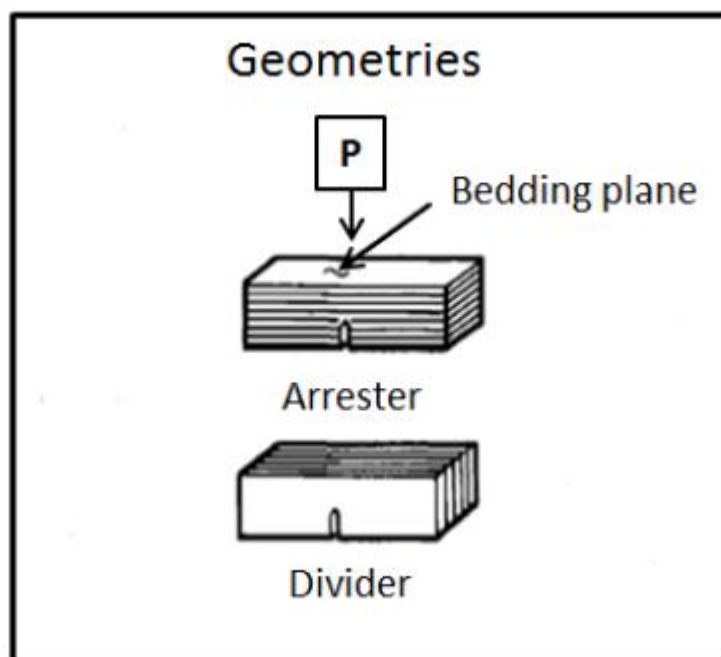


Figure 4. Bedding plane orientation for arrester and divider sample geometries (modified from Schmidt, 1977). P represents the load applied to the sample.

Fracture toughness is a material property which measures the ability to resist crack propagation (Lawn, 1993). Linear elastic fracture mechanics (LEFM) states that the stress intensity at a crack tip must exceed the critical stress intensity factor (i.e., fracture toughness) for crack propagation to occur. Fracture toughness is an important input parameter for hydraulic fracture modeling (Hsiao and El Rabaa, 1987) that can be determined from petrophysical analysis of acoustic logs (Jacot et al., 2010). Additionally, hydraulic fracture modeling has shown that layered contrasts in fracture toughness of adjacent strata influence fracture propagation and geometry (Thiercelin, et al., 1989)

In addition to the MFS, we tested the Cabrieroceras bed from the Bilger, Bald Eagle, and Handiboe wells. This low API, locally occurring marker bed is often a goniatite-rich, nodular limestone bed used for correlations in the outcrop belt of the Appalachian Basin [5]. The Union Springs Parasequence (PS)-3 surface in Figure 2 shows the low gamma ray bed identified as the Cabrieroceras in the Handiboe, Erb, and Bald Eagle wells becomes less distinct in the Bilger well and indistinguishable in the Yoder well. Consequently, we did not test a Cabrieroceras interval from the Yoder well. I sampled sandstones from the Mahantango Fm. from the Roy Adams and Bilger wells because this lithology is not present in the cored intervals of the other study wells.

A recent study by Jacot et al. (2010) details the methodology used in hydraulic fracture modeling for the Marcellus shale and presents values for fracture toughness and elastic modulus used in the modeling. Dynamic values obtained from petrophysical analysis of acoustic logs are converted to

static values for modeling purposes. The Jacot et al. findings will be compared to the results of this study. The elastic modulus values given by Jacot et al. are static and will be compared directly to the results of this study. In the case of fracture toughness, the dynamic Jacot et al. values will be halved, because dynamic values for fracture toughness are approximately double the static values (Bazan, written communication).

Preliminary Results

The fracture toughness of Middle Devonian core samples is strongly influenced by lithology, mineralogy, and organic content. The boxplots in Figure 5 show that sandstones of the Mahantango Fm. have the highest median fracture toughness while black shales of the Marcellus Fm. (i.e., the Oatka Creek, Upper Union Springs, and MFS intervals) generally display the lowest median fracture toughness. Carbonates from the Tully, Purcell, concretion, and Onondaga intervals have intermediate median fracture toughness values that consistently plot between the sandstone and black shale median values.

The relationship between fracture toughness, mineralogy, and organic content is depicted in Figures 5 and 6. Sample intervals determined to be quartz-rich (>46%) from XRD analysis display the highest median fracture toughness while clay and organic-rich intervals (>35%) have the lowest median fracture toughness. Samples with high carbonate content (>65%) show intermediate median fracture toughness values between the quartz and clay-rich sample intervals. The blue and red dashed lines on Figure 4 mark the high (i.e., BE 774') and low (i.e., Bilger 298') median values for clay and quartz-rich samples, respectively, excluding the anomalous Bilger 429' and Yoder 5699' intervals. Samples from Bilger 429' are categorized as clay- and organic-rich but plot closer to the quartz-dominated samples. However, Bilger 429' samples also contain significant quartz (39%) in addition to the high clay and organic content. Conversely, the Yoder 5699' interval is considered quartz-rich (66%) but has a lower median fracture toughness than the other quartz-dominated samples. Although samples from Yoder 5699' are quartz-rich with relatively low clay content (13%), they also have significant organic content (14% TOC by volume) that likely decreases the fracture toughness.

The experimental fracture toughness for the Oatka Creek and Purcell members of the Marcellus compare favorably to the petrophysically derived modeling values (denoted by the red stars in Figure 5). However, the modeling value used for fracture toughness of the Union Springs mbr. is lower than the majority of experimental median fracture toughness values for this member. Similarly, the median experimental fracture toughness for the Tully and Onondaga limestones are significantly higher than those used for hydraulic fracture modeling.

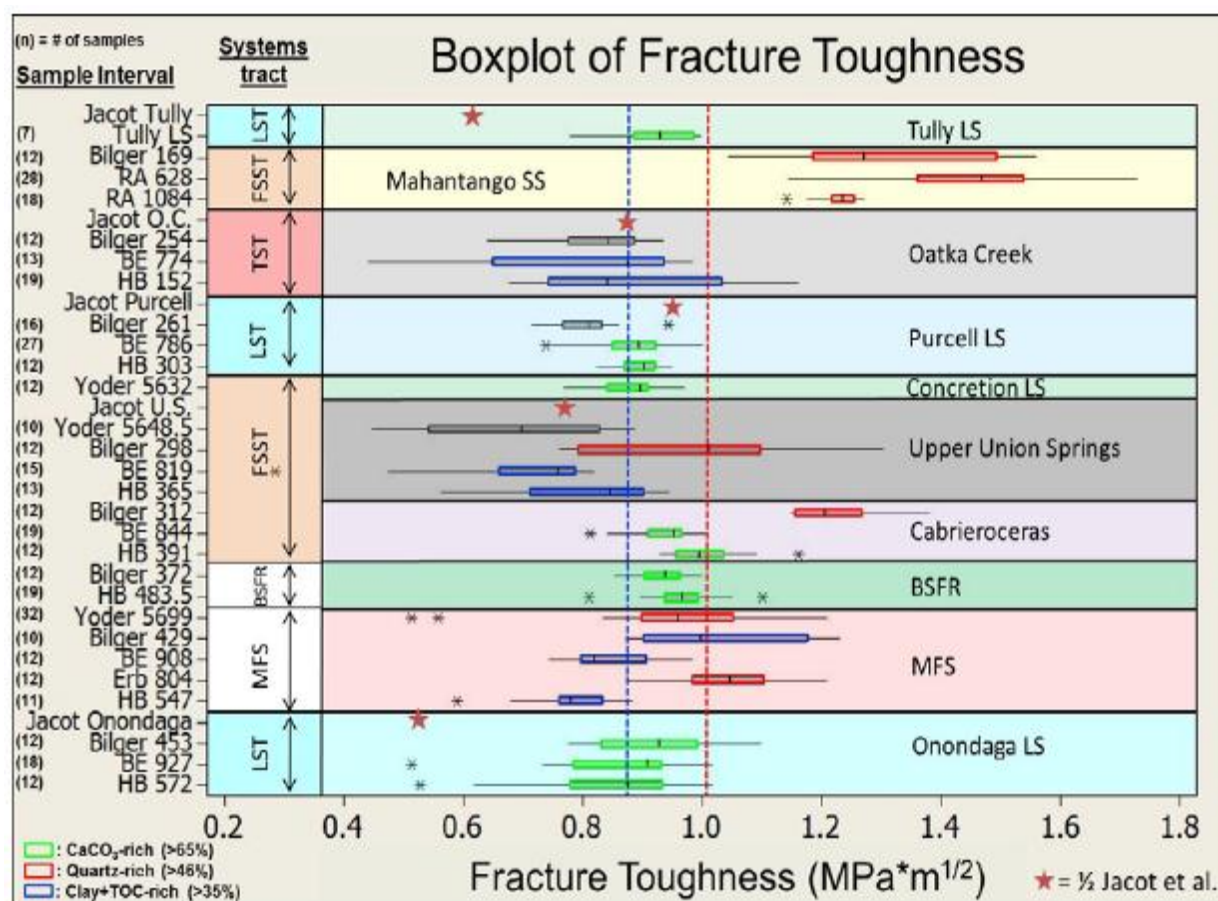


Figure 5. Boxplot of experimental fracture toughness values for Middle Devonian strata, ordered stratigraphically along the y-axis (with 'n' equal to the number of samples tested). The boxplots include data for the arrester and divider geometries for each interval. The systems tracts, interval colors, and names (Oatka Creek, Purcell, etc.) correspond to Figure 3. The red stars represent ½ of the Jacot et al. [6] dynamic values used for hydraulic fracture modeling. Asterisks denote outliers and the vertical black bar represents the median value. The blue and red dashed lines mark the high and low median values for clay-rich and quartz-rich samples, respectively (excluding anomalous median values for Bilger 429' and Yoder 5699'). LS = limestone, SS = sandstone, O.C. = Oatka Creek, U.S. = Union Springs, BE = Bald Eagle, HB = Handiboe, RA = Roy Adams, BSFR = basal surface of forced regression, MFS = maximum flooding surface, LST = lowstand systems tract, FSST = falling stage systems tract, TST = transgressive systems tract.

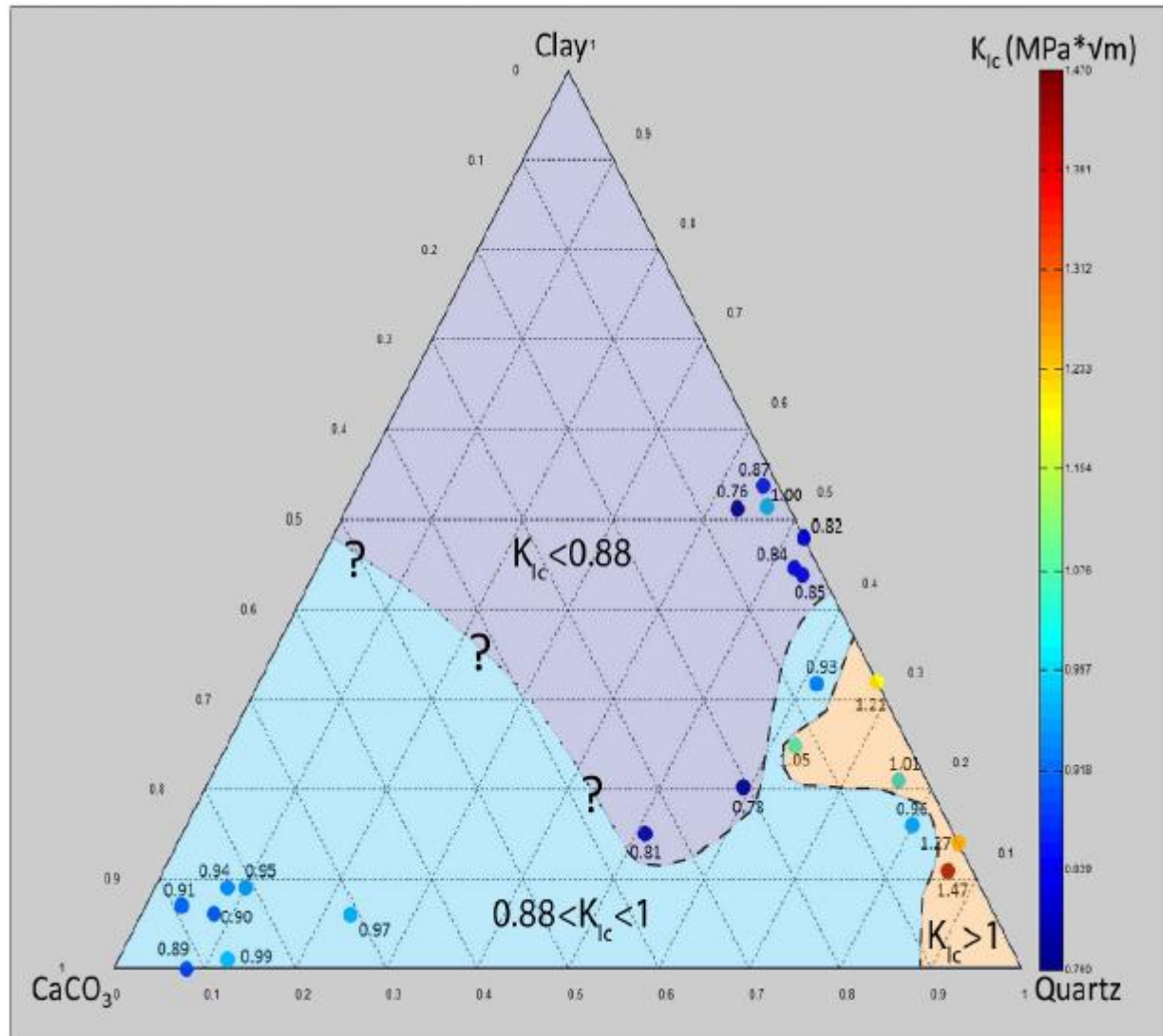


Figure 6. Ternary diagram depicting mineral composition (from XRD analysis) and fracture toughness magnitudes of the sampled intervals in this study. The three colored ploygons (orange, blue, and purple) represent areas of high, intermediate, and low fracture toughness, respectively (with one anomalously high value [i.e., 1.00] in the purple polygon). The XRD values for quartz, CaCO₃, and clay percent from XRD were re-normalized to obtain the values shown on the ternary diagram.

Conclusions

The fracture toughness of Middle Devonian core samples is heavily influenced by lithology, mineralogy, and organic content. Sandstones and quartz-rich samples have the highest fracture toughness while clay and organic-rich black shales have the lowest fracture toughness in this study.

Carbonates and calcareous shales (i.e. BE 844', HB 483.5') have intermediate fracture toughness values that plot between those of sandstones and black shales. Empirical results for the fracture toughness of Marcellus shale members generally agree with the Jacot et al. (2010) hydraulic fracturing modeling values but the experimental fracture toughness of the Tully and Onondaga limestones are significantly higher than those used for modeling purposes. Conversely, the empirical elastic modulus results match the Jacot et al. values for the Tully and Onondaga, but are considerably higher for the Marcellus shale members. This is the framework guiding our field tests and eventually the development of a geomechanical model for the Marcellus.

References

- Evans, K., Engelder, T., and Plumb, R.A., 1989, Appalachian Stress Study 1: A detailed description of in situ stress variations in Devonian Shales of the Appalachian Plateau: *Journal of Geophysical Research*, v. 94, p. 1729-1754.
- Hsiao, C. and El Rabaa, A.W., 1987, *Fracture toughness testing of rock cores*. Proceedings - Symposium on Rock Mechanics. **28**: p. 141.
- Jacot, R.H., Bazan, L.W., and Meyer, B.R., 2010, *Technology Integration - A Methodology to Enhance Production and Maximize Economics in Horizontal Marcellus Shale Wells*, in *SPE Annual Technical Conference and Exhibition*.: Florence, Italy.
- Kohl, D., 2012, *Sequence Stratigraphy and Depositional Environments of the Shamokin (Union Springs) Mbr., Marcellus Fm. and Associated Strata in the Middle Appalachian Basin*. Pennsylvania State University Geoscience Master's thesis,.
- Lash, G.G. and Engelder, T., 2011, *Thickness trends and sequence stratigraphy of the Middle Devonian Marcellus Formation, Appalachian Basin; implications for Acadian foreland basin evolution*. AAPG Bulletin, **95**(1): p. 61-103.
- Lawn, B.R., 1993, *Fracture of Brittle Solids (Cambridge Solid State Science Series)*. p. 517.
- Plumb, R.A., Evans, K. F., and Engelder, T., 1991, Geophysical log responses and their correlation with the bed-to-bed stress contrasts in Paleozoic rocks of the Appalachian Plateau, New York: *Journal of Geophysical Research*, v. 96, p. 14,509-14,528.
- Schmidt, R.A., 1977, *Fracture mechanics of oil shale*. United States (USA): Colo. Sch. Mines Press, Golden, Colo., United States (USA).
- Slatt, R.M. and Abousleiman Y., 2011, *Merging sequence stratigraphy and geomechanics for unconventional gas shales*. *Leading Edge (Tulsa, OK)*, **30**(3): p. 274-274-282.

Thiercelin, M., Jeffrey, R.G., and Naceur, K.B., 1989, *Influence of Fracture Toughness on the Geometry of Hydraulic Fractures*. SPE Production Engineering, 11 p.